AN INNOVATIVE TOOL TO STUDY AND OPTIMIZE RACING YACHT APPENDAGES USING FLUID-STRUCTURE INTERACTIONS

Rémy Balze[1,2], Nedeleg Bigi[3], Kostia Roncin[3], Jean-B. Leroux[3], Alain Nême[3], Vincent Keryvin[4], Antoine Connan[1,4], Hervé Devaux[1] and Denis Gléhen[1],

[1]GSEA Design, 1 rue Galilée, F-56270 Ploemeur, France
e-mail: remy@hds-design.com, web page: http://www.gseadesign.com/

[2] Univ. Bretagne Occidentale, FRE CNRS 3744, IRDL, F-29200 Brest, France
e-mail: remy.balze@univ-brest.fr - Web page: http://www.irdl.fr

[3] ENSTA Bretagne, FRE CNRS 3744, IRDL, F-29200 Brest, France
e-mail: nedeleg.bigi@ensta-bretagne.org - Web page: http://www.irdl.fr

[4] Univ. Bretagne Sud, FRE CNRS 3744, IRDL, F-56100 Lorient, France
e-mail: vincent.keryvin@univ-ubs.fr - Web page: http://www.irdl.fr

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Abstract. GSEA Design developed a fluid structure method (FSI) suitable for early design stage of appendage with complex shapes dedicated to the America's Cup flying catamarans. The aerodynamic loading and the boat weight are counteracted by the appendages and mainly the dagger-board. Consequently, the appendage structural design is very critical. Based on a 3D lifting line and a modified beam element method, the GSEA Design FSI method takes less than one minute to compute. An illustrating example on a L-shape appendage shows that the FSI results compared to a non-FSI results can be particularly different at the elbow. Thanks to the short computational time of the method, multi-objective optimizations can be performed. For instance, a second illustrating example shows the optimization of the appendage weight and stiffness.

1 INTRODUCTION

A sailing boat is a wind driven vessel in permanent equilibrium between two fluids: air, that provides the power required for its movement through sails or wingsails, and water, on which the sailing boat is based. In addition to hulls, structural parts that allow this support are appendages: rudders, foils, daggerboards. . .. The three last America's Cup (33^{th}, 34^{th} and 35^{th} led engineers of GSEA Design to design appendage in order to improve performance and stability of sailing catamarans of teams such as *Oracle Team USA*, *Artemis Racing* and *Groupama Team France*. Although, the balance of these sailing boats can be relatively stable when their hulls remain in the water, it will be more precarious when they fly. The hydrodynamic loading of an appendage can lead to large deformations. When this appears, a coupling between the hydrodynamic loading and the appendage shape is necessary to compute the equilibrium of an appendage. Consequently, a Fluid Structure Interaction (FSI) model should be applied. From a structural engineering point of view, the aims of GSEA Design engineers with this tool is to :

- Know the appendages equilibrium in water flow
- Get closer to the real load-cases applied on the boat
- Optimize appendage structure to stabilize boat fly

Since an optimization process requires several FSI calculations, a fast method in term of CPU time is needed. The flow around an appendage is generally three dimensional and lead mostly to bending and torsional deformations and displacements. A 3D RANS method for the flow computation coupled with a 3D finite element method could be appropriate to model the physical phenomenon. Nevertheless, these methods are out of the scope of the paper due to their long CPU time. A faster and consistent manner to deal with the FSI calculation in order to optimize a structural design is the use of a non linear 3D lifting line [2] coupled with the Timoshenko beam element method [5]. Duport et al. [2] show very accurate results for small angle of attack compared to the 3D RANS method. Moreover, it can be shown that the bending and the torsional stiffness of the structure has a high impact on the equilibrium. Consequently, a pseudo-analytical method has been developed to evaluate these properties. GSEA Design has

Figure 1: *Groupama Team France* AC45 Test (©Eloi Stichelbault / *Groupama Team France*)

Figure 2: *Artemis Racing* AC45 Turbo (©Eloi Stichelbault / *Artemis Racing*)

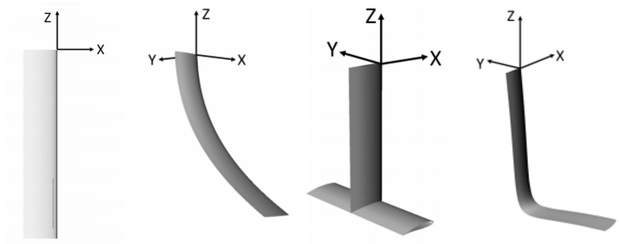

Figure 3: Different types of appendages : *Straight-Shape*, *C-Shape*, *T-Shape* and *L-Shape*

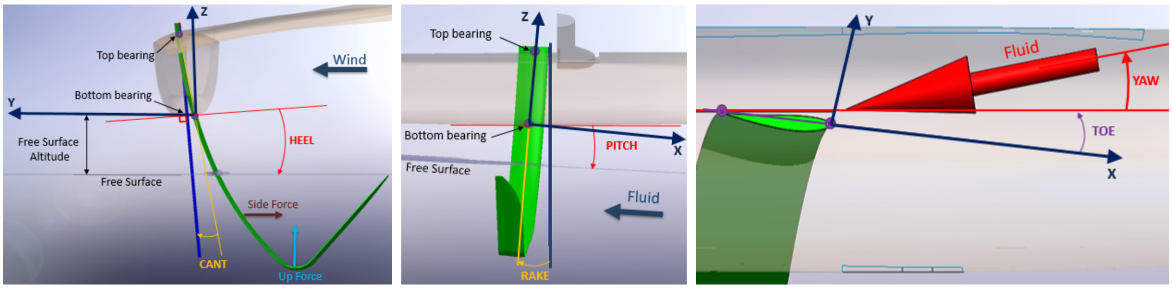

Figure 4: Appendage coordinate system

thus developped a tool for appendage design using FSI calculation and called *Sofia* [1].

In a first part, the FSI method and the pseudo-analytical method to evaluate the bending and torsional stiffness are introduced. Then the iterative numerical scheme to reach equilibrium is presented. In a second part, two illustrating examples are presented, one on a simple FSI calculation and a second on the optimization of a dagger-board structural design in term of mass and stiffness.

2 APPENDAGE MODELING

2.1 Appendage Description

An appendage is a part of the boat beneath the hull. Classical appendages are *rudders* which enables to steer the boat and *dagger-boards* which counters the leeward thrust of sails (Figure 3).

Since the aim is to design a flying boat, appendages able to produce a vertical lift force are used: *T-Shaped Rudder* and *L-shaped dagger-boards* (Fig. 3). In addition to their vertical lifting force, they produce transverse components forces needed for the global equilibrium of the sailing boat.

An appendage can be seen as a simple supported beam. The appendage orientation is parametrized with three angles depicted in Fig. 4. Altitude over the free surface is also an important parameter that can modify the load-case distribution.

For a L-shaped foil, its vertical part of a foil is commonly called *shaft* whereas its horizontal part is called *tip*.

[1] **S**tructural **O**ptimisation using **F**luid-structure **I**nteractions for **A**ppendage design

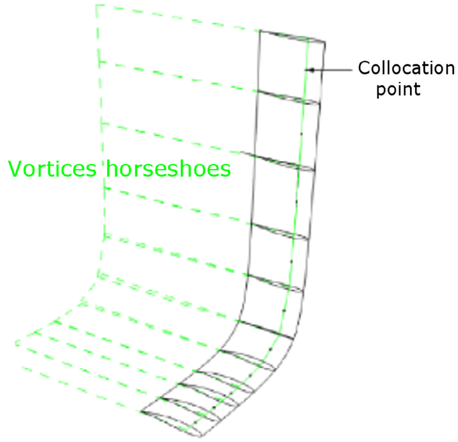

Figure 5: Vortex distribution along a wrap span

2.2 Hydrodynamic Model

The fluid flow around the sections along the span, except near the tip, behaves essentially as two-dimensional flow for lifting bodies with high aspect ratio. However, the pressure difference between intrados and extrados creates a more and more significant flow component along the span as we approach the end of the tip. This creates a flow enrollment around the tip edge creating the so-called tip vortex, which can be source of significant loss in lift and energy. Consequently, the fluid flow around the appendage should be considered as three-dimensional to be accurate. This phenomenon is particularly well represented on a straight appendage with the so-called lifting line method proposed by Prandtl [1] in 1918.

However, Prandtl lifting line method is strictly applicable only on straight span appendage. Since appendages used on high performance sailing boats are curved in order to allow the boat to fly over water, the non linear 3D lifting line method proposed in [2] (see also [4]) is here applied. Indeed, this extension of the lifting line theory is an iterative numerical method which takes into account the evolution of the dihedral and sweep angles. In Figure 5, the fundamental difference between the Prandtl's lifting line method [1] and the method proposed by Duport et al. [2] is that the bounded vortices are no longer aligned and parallel. The induced velocity at any collocation point may be dependent of the other bounded vortices. Then, using the iterative method presented in Anderson [3] to calculate the vorticity, the non-linearity of section lift coefficients, for example computed with 2D RANS method, can be taken into account.

2.3 Structural Model

The hydrodynamic model is coupled with the Timoshenko beam model [5], which takes into account shear forces.

Figure 6 shows the element description : an element joins the nodes I and J. At each node corresponds a section, a laminate and mechanical properties such as:

- Young and shear modulus
- Section and reduced section considering local coordinate system
- Bending and torsion inerties considering local coordinate system

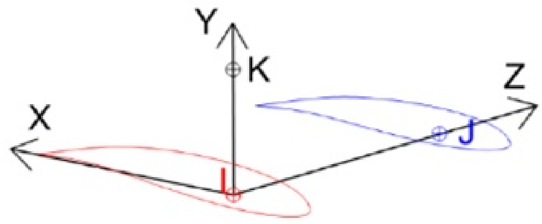

Figure 6: Beam model in *Sofia*

Section angle of attack is highly coupled with bending and torsion of the appendage. As a result, an accurate evaluation of the bending and torsional stiffness of finite beam element model has a high impact on the load-case, and so on the FSI calculations. Consequently, a pseudo-analytical method has been developed in order to obtain a good evaluation of bending and torsional stiffness of a composite material section [5][6][7]. For instance, torsion stiffness of fairing is the same as thin profile [7] and can be expressed as :

$$GI_{zz} = \frac{4 \cdot S^*}{\sum_i (\frac{l_i}{G_i \cdot t_i})} \tag{1}$$

The mechanical properties of section obtained with this pseudo-analytical method has been validated using 3D finite element analysis.

3 FLUID STRUCTURE INTERACTION NUMERICAL SCHEME

3.1 Classical Iterative Process

GSEA Design focused on hydro-elastic phenomena and FSI on lifting structures in water in order to provide answers to performance, efficiency and stability issues. Here, the fluid-structure interactions model developed is a quasi static and iterative process (Figure 7). At each iteration, an equilibrium is reached. The assumption are :

- Slender structure
- Sections are not deformable
- Small perturbations (linear stiffness matrix)

A hydrodynamic loading is firstly calculated, considering the appendage attitude in the fluid flow. This hydrodynamic loading is then applied to the non-deformed or deformed geometry of the beam model. The iterative process ends when the convergence criteria, between two successive fluid-structures loops, is lower than a user defined convergence criteria. At the end, the internal forces and deformed geometry calculated allow to design the appendage regarding stresses or stiffness.

3.2 Target Loads

A second type of calculation considers side force denoted by F_y and lift force denoted by F_z as inputs. *Sofia* is able then to optimize appendage position in the fluid in order to reach the target loads. It can give for instance the corresponding Rake and Yaw angles for the boat to

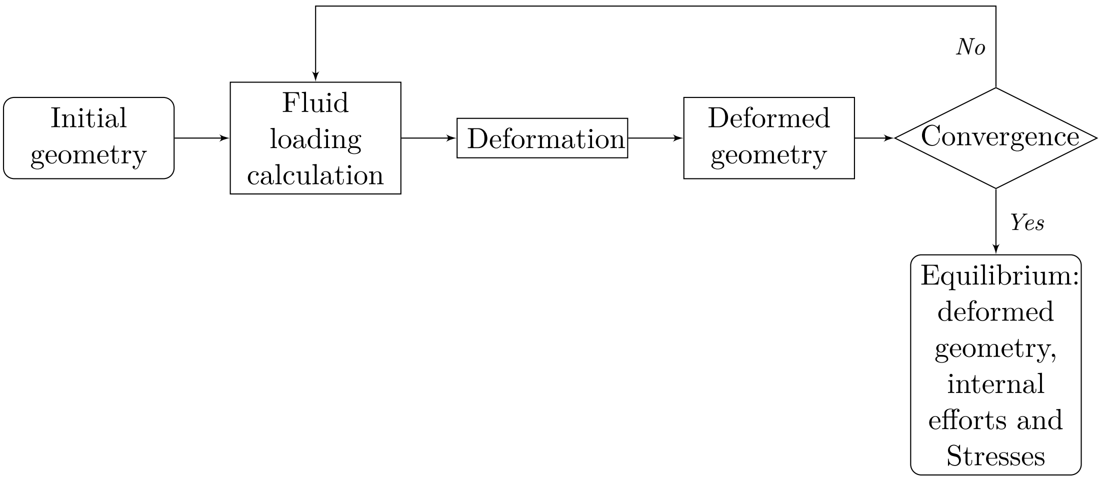

Figure 7: Numerical scheme of the quasi steady fluid structure interaction

Figure 8: Groupama catamaran Class C *(Groupama Sailing Team)*

take off the free surface:

$$\begin{pmatrix} F_y(yaw, rake) \\ F_z(yaw, rake) \end{pmatrix} - \begin{pmatrix} F_{y-target} \\ F_{z-target} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (2)$$

Equation (2) is solved numerically. This method works with all the developed hydrodynamic loading and calculation methods.

4 ILLUSTRATING EXAMPLE

In order to prepare the 35$^{\text{th}}$ America's Cup, *Franck Cammas* and *Groupama Sailing Team* have decided to build a C Class catamaran (Figure 8). These catamarans are powered by a 27.8 m^2 wing-sail. They are 7.62 meters length and 4.20 meters width. Groupama C Class has been designed with a close collaboration between several architects and has won two times the *Little Cup* (2013 and 2015).

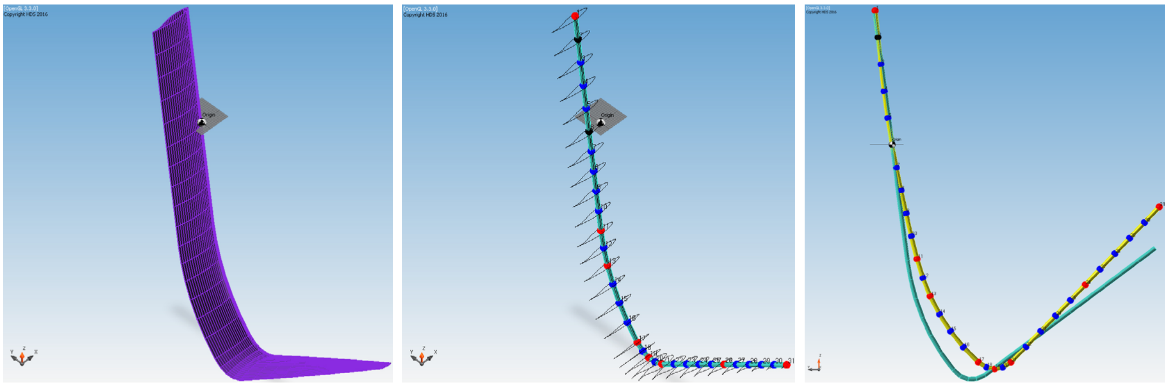

Figure 9: Class C foil geometry (on the left and middle) and deformed geometry (on the right)

4.1 Fluid Structure Interaction Results

Each load-cases are characterized by a boat speed, an altitude over free surface and a Cant angle. *Sofia* can then calculate yaw and rake angles. The corresponding load-case enables to design this appendage (Fig. 9) regarding stiffness.

Figures 10 and 11 show respectively the bending moment and the shear stress along the span for two method of calculation. The first method in red line represents the results without FSI, *ie*, only the first loop of the FSI iterative algorithm Fig. 7 is performed. The second method, in blue line, represents the result with full FSI calculation.

For this illustrating example, the FSI calculation leads to lower internal forces at the bottom bearing and at the elbow, the connection between the tip and the shaft. Therefore, by considering this more accurate loading distribution, the appendage design can be lighter.

In term of CPU time, the FSI computation takes around one minute on classical PC.

4.2 Optimization results

Optimization can be proceeded with *Sofia*. In this illustrating example, UD quantity in appendage stock is optimized, the objective is to minimize mass and to maximize stiffness regarding failure stresses. The multi-optimization results are plotted in Fig. 12 in term of Pareto-efficient frontier. The best designs are distributed near the red curve. It can be shown that a lighter appendage has a lower stiffness and a stiffer appendage is heavier. The final design is chosen in agreement with the requirement specifications and the designer experience.

The necessary calculation the Pareto-efficient frontier in Fig. 12 takes around 6 hours on classical PC.

5 CONCLUSION

A fast and efficient fluid structure interaction method has been presented. This method is based on an iterative algorithm using a 3D non-linear lifting line for the hydrodynamic loading and a modified beam element method. The beam element method has been modified in order to represent with good accuracy the bending and torsional stiffness. It has been shown that it is necessary to tune the initial position of the appendage in order to reach a target load. The

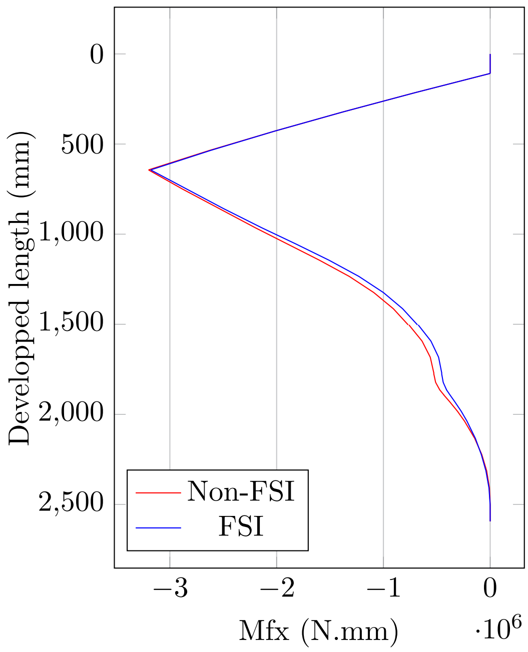

Figure 10: Bending moment distribution along the span

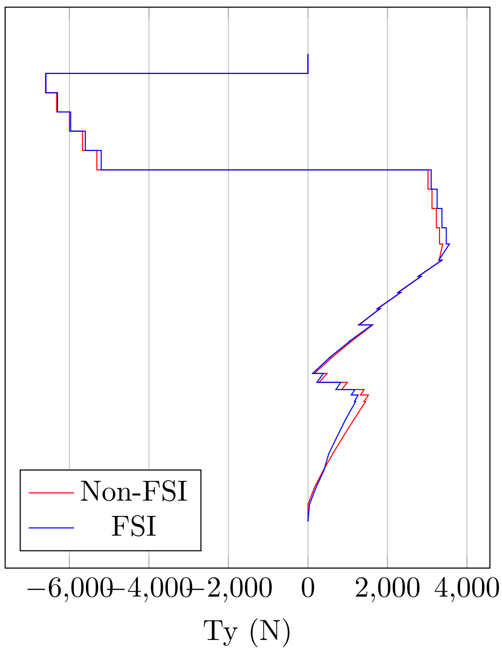

Figure 11: Shear force distribution along the span

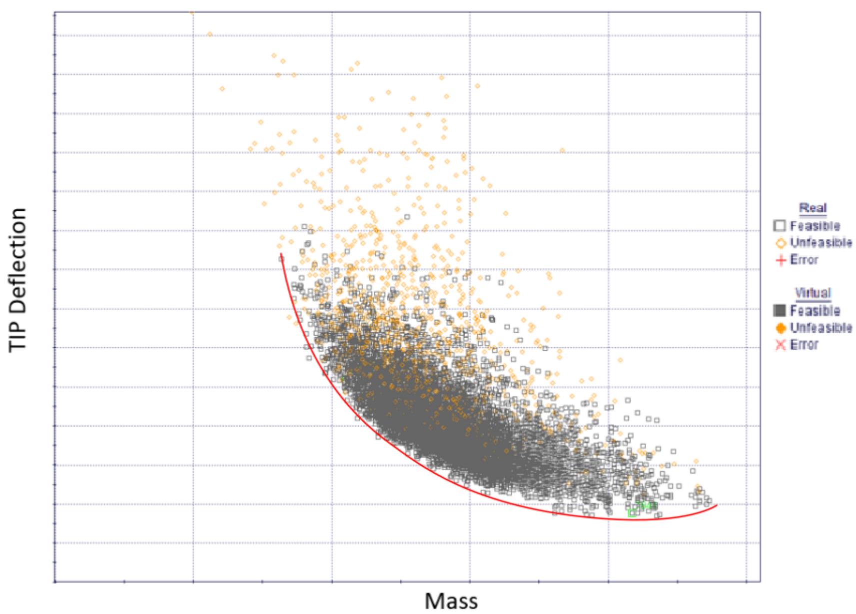

Figure 12: Pareto-efficient frontier to optimize UD quantity along an appendage's span

two illustrating examples shows that the method is fast in term of computation time, which is necessary to study a wide range of design.

A simple multi-objective results has been presented in order to optimize the appendage mass and stiffness. Further investigations to optimize the boat speed and stability can be performed with a velocity prediction program coupled to the presented FSI method.

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